

Microgrid protection using system observer and minimum measurement set

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SUMMARY

Microgrids work in two modes, grid connected and islanded. Short circuit levels in islanded mode tend to be small compared to those in grid-connected mode. Moreover, power flows in microgrids are not always unidirectional. For these reasons, it is difficult to protect microgrids using relaying strategies traditionally used in distribution systems. In this paper, a new technique is presented which uses a state observer to detect and identify faults that occur within the zone of protection, regardless of whether the microgrid is islanded or grid connected. The proposed system can be centralized or decentralized. In addition, based on system observability, the required number of measurements can be reduced, thereby reducing the cost of the proposed protection system. It is possible to devise a low-cost protection system using the proposed approach. The performance of the proposed method in protecting IEEE 34 node test feeder is demonstrated on an Alternative Transient Program (ATP). The proposed approach is shown to be effective in grid-connected and islanded modes. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: microgrid; observer; protection; alternative transient program (ATP); phase observer; earth fault observer

1. INTRODUCTION

Microgrids are designed to work in two modes, utility connected and stand-alone (islanded). In the event of failure of the utility grid, a microgrid should be able to operate in islanded mode. The switching between the two modes guarantees continuity of supply to critical loads, but a traditional protection system may not be effective in both modes [1].

One issue is that there would be smaller short circuit currents in islanded mode [2]. Therefore, the protection system may not detect all faults. For instance, overcurrent relays work in the current–time characteristic, so the trip time for certain faults may be very large or infinity in case of islanded mode. Further, the power flows in feeders may differ in direction under different operating conditions. For these reasons, a suitable protection system is necessary that would adapt to the different operating conditions, or be indifferent to the operating condition. Protection systems normally used in distribution systems may not be effective in microgrids.

Much research has been reported on this issue and several solutions have been suggested. The use of digital relays with communication systems in [3] offers an effective solution, but in some cases its cost may be unacceptably high. In [4], a d - q transformation method is used for fault detection in a microgrid system in which all micro-sources are equipped with power electronic interfaces. Reference [5] proposes an integrated control and overcurrent protection interfacing to the substation measurement devices and microgrid components through a substation optical communication network. References [6] and [7] propose that the protective functions should be part of the distributed generator (DG).

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This type of operation needs an adaptive protection system which can adapt to network changes, like switching between two modes of operation (grid connected and islanded) and source outages, or protection that will be independent of such changes. In this paper, we propose a new protection scheme using a state observer. The state observer would not be affected by changes in network topology. In addition, it is possible to achieve this protection using a minimized measurement set. Consequently, the overall cost of a protection system based on the proposed scheme would be significantly lower than that of using conventional relays to perform adaptive protection. In measuring the end voltages, there would be common voltage measurements for some branches. In addition, sources and loads are already supplied with their measurement devices for voltages and currents. Sending and receiving data (measured data and trip signals) in this system would need communication media. In centralized control schemes, the observer can be present at the distribution management system and can use existing communication channels. Sending measured data through the communication media would be in case of faults only. For decentralized scheme, the observer-based protection relay is positioned on one end, and it receives the required remote end information (voltage) of protected zone through a communication channel.

The observer-based fault detection can be implemented by dividing microgrids into zones. Each zone is observed separately using four observers, three for phases and one for earth fault. (On a secondary feeder, one observer per zone would suffice.) In case of a fault, it would be easy to identify the faulted zone and the faulted phase. Hence, fault detection and identification conditions can be met using the observer-based fault detection technique.

This research is a continuation of studying the observer technique proposed in previous work [8] which is a protection system for microgrids. New additions, adjustments, and corrections have been made; these include earth fault observer, minimum measurement placement, and transformer protection using the observer technique.

State space representation helps in describing the connected system behavior and can be used to analyze the power system network transients [9]. In addition, the state space representation is used in building observers which are used for estimating system behavior. The observer theory is used as a fault detector in many different systems [10] and [11], but they need many measurements for different states like angle, current, and voltage. The method presented here reduces the necessary number of measurements by two means: (i) use of the system model in a manner that requires voltage and current measurements from only one end of each zone, and (ii) use of the system observability properties to place the measurements in a minimum number of locations as determined by the method described in [12]. In this research, the representation of states is simple and only the current measurement is used as a state.

The proposed protection system for microgrids is easy to build with minimum measurement devices, adaptive with the network changes, selective for different kind of faults, and provides fast operation in the presence of faults (grading time is not required).

2. CONSIDERATIONS IN MICROGRID PROTECTION

Two challenges should be considered in designing a protection system that is effective in both grid-connected and islanded modes.

First, sources in microgrids are renewable energy sources that often contain inverters. Output currents of inverters are limited values (normally twice their rated current); then, upon occurrence of a fault, the contribution currents of these distributed sources would not be sufficient to pick up the first stage (instantaneous stage) of the ordinary overcurrent protection relay, while the second and third stages would take a long time to operate. In grid-connected mode, current levels would be very high compared with those in islanded mode. There is therefore a huge difference in fault current levels between grid-connected and islanded modes.

Second, the high cost of numerical protection relays, like differential and distance relays, makes it expensive to protect microgrids using those types of relays.

Therefore, integrating (centralizing) an adaptive protection system with the control system is still a good choice. In addition, the observer-based protection system requires fewer measurements than most

other protection systems. A communication system is necessary to supply data from the network to the observer-based protection system.

Once the fault is detected and identified, the trip decision can be sent via the communication system to specific circuit breakers to isolate the fault. Such a system would be very fast in isolating the faulted zone since it does not need any coordination time.

3. THEORETICAL DEVELOPMENT OF OBSERVER-BASED FAULT DETECTOR

The basic idea of an observer-based fault detection technique is to reconstruct the outputs of the system from the measurements or subsets of the measurements with the help of an observer, and to use the estimation error as a residual for the detection and isolation of the faults [9–11], [13,14].

Observer-based fault detection technique is implemented by dividing microgrids into zones and design three identical phase observers and one for earth fault for each zone. So, in case of phase faults, the faulted zone, specifically the faulted phase, would be identified easily. Hence, the fault detection depends on a bank of observers and only the faulted zone generates a residual output on its observer. For ground faults, both phase and earth fault observers can detect the fault. More description for the behavior of the observer-based protection system with earth faults will be discussed in section 4.

To construct an observer, some measurements of inputs and outputs are necessary [15]. Therefore, dividing the microgrid into separate zones could be based on the sources and measurement positions. Loads on the other hand can be inside the zone (in-zone loads) as shown in Figure 1a, and their values should be taken into account when designing the observer since the load value, in this case, would appear in the observer's residual. Voltage and current measurement would be used as input and output measurements, respectively. These quantities should be measured at the line itself because loads and sources can disconnect at any time.

In Figure 1b, representing the model of one protected zone, R and L are the resistance and inductance of the transmission line between two nodes of feeding and loading. This means that the zone has been chosen to include two points which may have sources and loads. Since feeder lengths in microgrids are not very long, the mutual impedances are small and can be neglected. In this circuit, u_1 and u_2 are the phase voltages at the two ends of the zone, and they are defined as inputs. The measured line (inductor) current is defined as the output. Hence, the following equations describe the state space representation of this circuit,

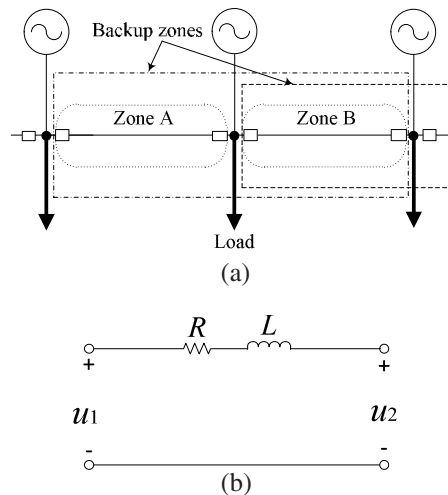


Figure 1. A representation of one zone: (a) Single line diagram with main and backup zones, (b) Circuit of one zone.

$$\begin{aligned}
-u_1 + u_R + u_L + u_2 &= 0 \\
Ri + L \frac{di}{dt} + u_2 - u_1 &= 0 \\
\frac{di}{dt} &= \frac{-R}{L} i + \frac{1}{L}(u_1 - u_2)
\end{aligned} \tag{1}$$

Let $x = i$; then $\dot{x} = \frac{di}{dt}$ and the output $y = i = x$ and $u = u_1 - u_2$. Therefore, the state space model will be as follows,

$$\dot{x} = Ax + Bu \tag{2}$$

$$y = cx \tag{3}$$

where $A = \frac{-R}{L}$, $B = \frac{1}{L}$ and $C = 1$

Now, the observer is developed as follows. Let $\hat{x}$ is the state estimate and $(y - \hat{y})$ is the output error; then, the observer (estimator) is

$$\dot{\hat{x}} = A\hat{x} + Bu + k(y - \hat{y}) \tag{4}$$

Where k is the gain, $\Delta \hat{x} = k(y - \hat{y})$, and $\hat{y} = C\hat{x}$; then, the output error will be

$$e = r = y - \hat{y} = y - C\hat{x} = C(x - \hat{x}) \tag{5}$$

By inserting (5) in (4), the state observer would be

$$\dot{\hat{x}} = (A - kC)\hat{x} + Bu + ky \tag{6}$$

Therefore, the residual r is the error obtained by subtracting the estimated from the measured outputs; the block diagram of the state observer is shown in Figure 2a and the protection framework is described in Figure 2b.

Let the state error be $\tilde{x} = x - \hat{x}$, then $\dot{\tilde{x}} = \dot{x} - \dot{\hat{x}}$. This is the error between the real process and the observed states. Hence, if the process and the model parameters are identical, then by using (2) and (6), the equation

$$\dot{\tilde{x}} = (A - kC)\tilde{x} \tag{7}$$

can be developed. Therefore, the state error vanishes asymptotically, since $\lim_{t \rightarrow \infty} \tilde{x} = 0$ for any initial state deviation $[x(0) - \hat{x}(0)]$ if the observer is stable, which can be reached by proper design of k [15]. Using the pole placement method, k should be chosen such that the real part of every $[\lambda(A - kC)]$ is negative, where λ is an eigenvalue. In our case, the dimension of the matrix A is one by one; therefore,

$$\begin{aligned}
(A - kC) &= \frac{-R}{L} - k \\
\lambda I - (A - kC) &= 0 \\
\lambda &= (A - kC)
\end{aligned}$$

Thus, k is designed using the desired eigenvalue that meets the criteria. This criterion is to make the observer more stable so that the damping response is faster than that of the process. This would be achieved if the eigenvalue were moved to the left half of the s -plane.

Faults f_L act on the output error e according to the observer dynamics $[sI - (A - kC)]^{-1}$. The static deviation for a step-change f_{L0} becomes

$$\lim_{t \rightarrow \infty} e(t) = e(s=0) = -C[(A - kC)]^{-1} L f_{L0}(s) \tag{8}$$

From (8), it is clear that the gain k has an effect on the residual's value.

Because the residual is a function of the observer gain, the residual value will be suppressed for high gain or magnified for low gain. In such cases, the residuals do not provide an accurate indication of fault amplitudes. Reference [16] presents an approach, which is implemented in this work, to avoid the effect of gain on residual. The method depends on pre-multiplying the residual by the factor $(I - CA^{-1}k)$. Then, the final value of the residual will be

$$r = e(s=0) = -CA^{-1} L f_{L0}(s) \tag{9}$$

In the next section, we show how the proposed protection scheme responds to different fault types.

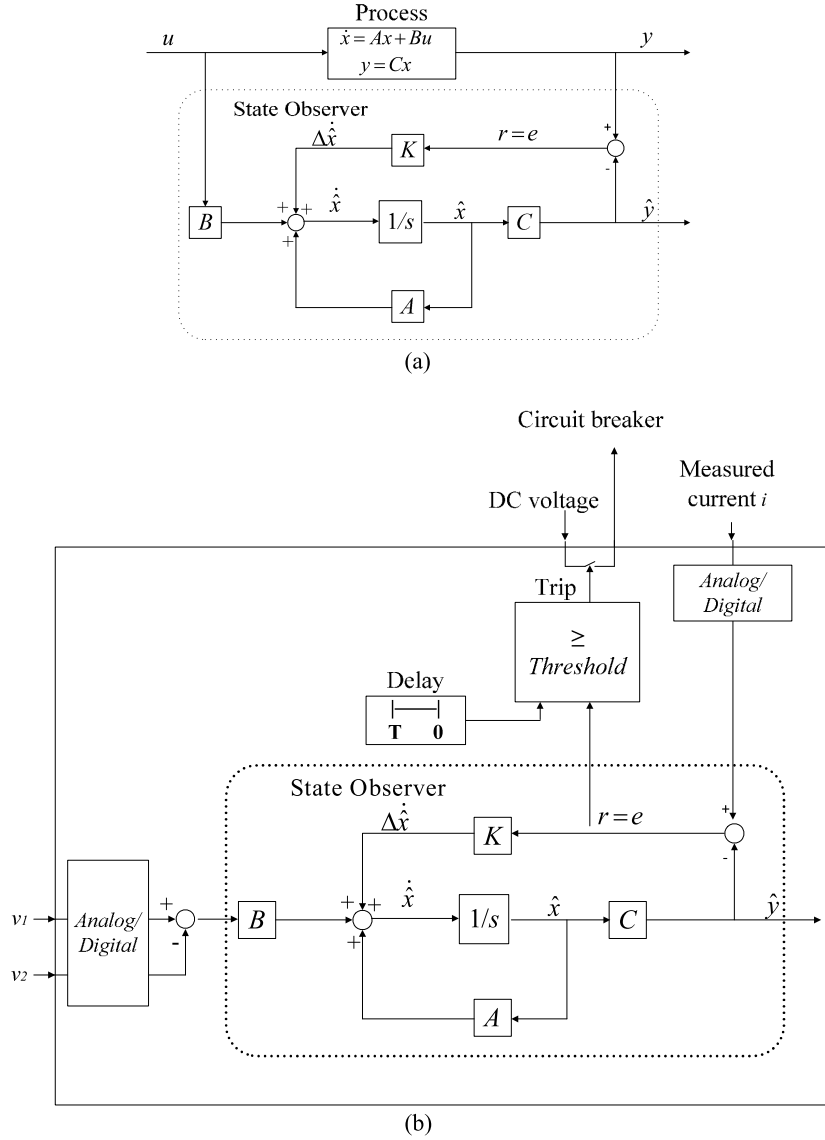


Figure 2. (a) State observer as a fault detector, (b) Protection framework.

4. APPLICATION TO MICROGRID PROTECTION

4.1. Observer-based fault detector behavior with different kinds of faults

When a three-phase fault occurs in a protected zone, the three observers of those three phases will have values in their residuals even if the microgrid is islanded. This occurs for the phase to phase faults as well. The value of the residual depends on the position of the fault in the protected zone.

Since the network impedances change in case of ground faults as shown in Figure 3, a separate observer is designed based on the zero sequence impedance, voltages, and currents of the protected zone and this observer is called Earth Fault Observer. Therefore, the design of earth fault observer should consider the zero sequence impedance to find A and B.

To decouple the zero sequence currents and voltages, measurements should be taken from the neutral point of the current transformers (only one end CTs) and the open delta of the voltage transformers (summation of the three-phase voltages gives the same result) in both ends as shown in Figure 4. The phase observers can detect the earth fault, but the earth fault observer cannot detect the phase faults. The change in the network impedances allows the phase observers to detect ground

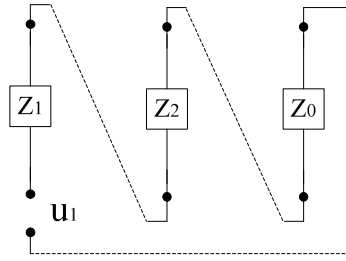


Figure 3. Equivalent network of single line to ground fault.

fault even if they are in the neighbor zones, but only the earth fault observer for zone in fault detects that fault. Therefore, the faulted zone can be recognized easily once its phase and earth fault observers detect the ground fault in their residuals. By setting a margin time between phase and earth fault observers, the ground fault can be detected and isolated before the phase observers can. This margin can be the same value for all zones and no grading time is necessary between zones. For example, for earth fault observer of all zones, trip time can be adjusted to instantaneous value and any larger values for phase observers. Because the technique of the observer-based protection system relies on the error value, the residual of the earth fault observer can detect ground faults even if they are through high impedance.

4.2. Minimum measurement placement

In this section, the problem of minimizing the number of measurement sensors that give enough fault information is investigated. This approach is based on maintaining system observability under all operating conditions. Although observability varies with changes in the microgrid configuration, the minimum measurement placement is still possible. In this research, source outages do not affect on the observability, but feeder outages do. Therefore, taking feeder outages into consideration helps in placing current and voltage measurements.

There will be one observer per phase of the protected zone and that enables identification of the fault type (phase to ground, phase to phase, and three-phase fault). As a result, for each zone, there will be

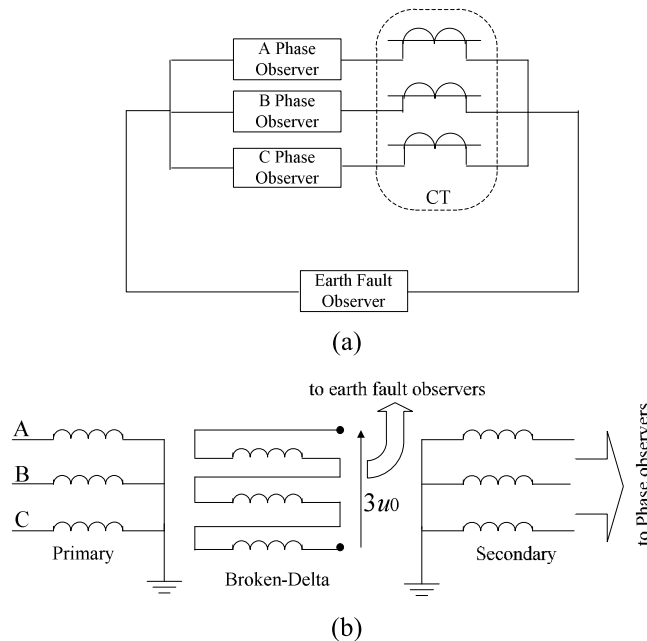


Figure 4. Phase and earth fault observers connections of (a) current transformers, (b) voltage transformers.

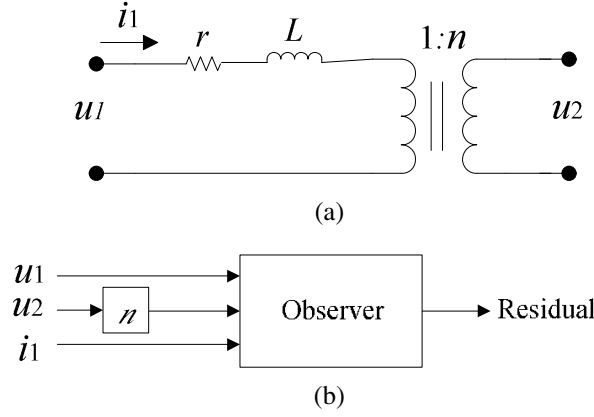


Figure 5. (a) One phase of a power transformer with zero shift angle, (b) single phase observer-based protection relay related to circuit (a).

four observers, three for phase faults and one for earth fault. Therefore, all these observers need input and output measurements.

Reference [12] describes a method of analyzing the observability and placing the phasor measurement units (PMU) in a network. PMUs provide voltage and current information that are synchronized by global positioning system (GPS). Each PMU can measure the bus voltage and all currents of the connected lines to that bus. For the proposed protection system, it is not necessary to use PMUs; any means of current and voltage measurement is valid and there is no need to use GPS time stamps in the proposed system.

For an n -bus network, the placement is achieved as follows [12]:

$$\begin{aligned} \min \sum_i^n w_i \cdot x_i \\ f(x) \geq \hat{1} \\ x_i = \begin{cases} 1, & \text{if a PMU is installed at bus } i \\ 0, & \text{otherwise} \end{cases} \end{aligned} \quad (10)$$

where w_i is the cost of the PMU installed at bus i and $f(x)$ is a vector function, which has non-zero entries if the related bus voltage observable using the given measurement set and zero if are not observable. $\hat{1}$ is a vector which all its entries are ones.

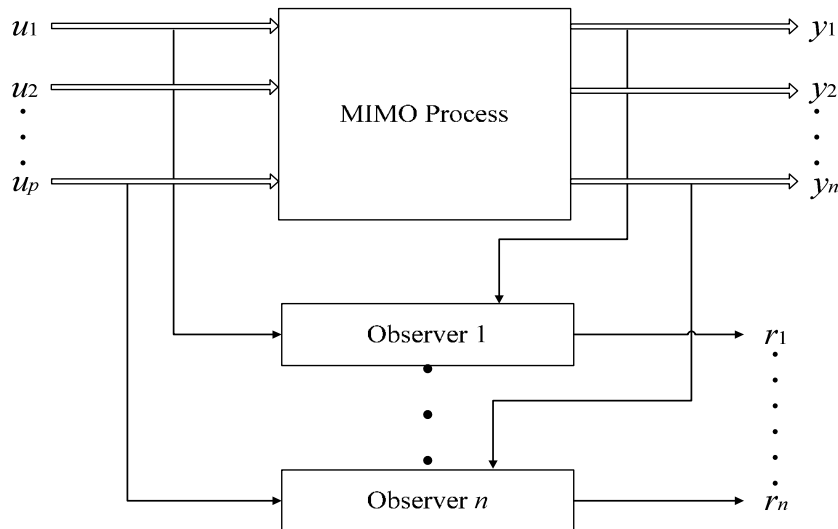


Figure 6. Multi observer system (bank of observers).

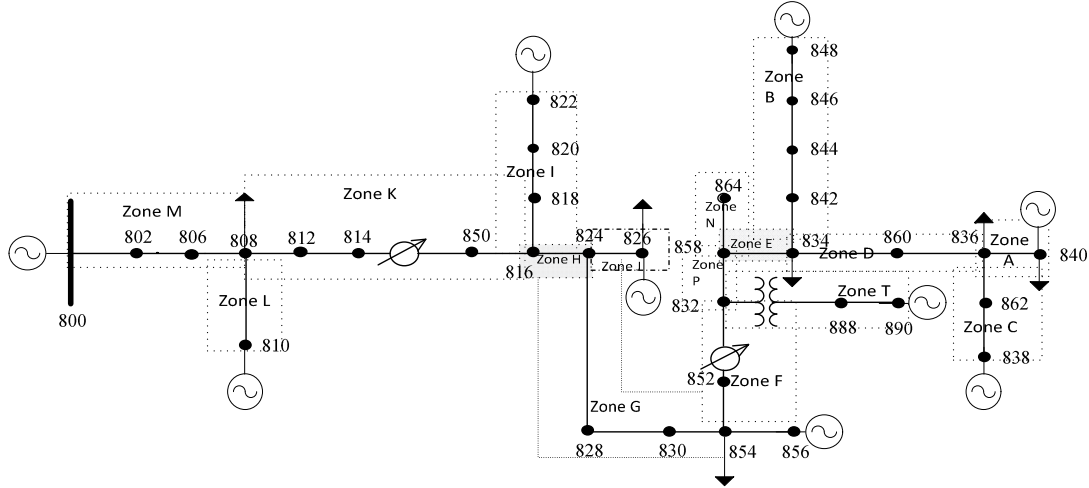


Figure 7. IEEE 34 node test feeder with protection zones.

The next step is to estimate unmeasured quantities. Once the sensors are placed, the unmeasured quantities can be estimated using Kirchhoff's laws (KVL and KCL). Normally, in control design, it is mandatory to find estimates of state variables that are not accessible by direct measurement. For a linear system, state vector can be approximately estimated by constructing an observer which can be built from outputs and inputs of the original system. The system that has state vector of an n th order system with m independent outputs can be estimated using an observer of order $n-m$ [15]. In this paper, there will be multi observer system which some of its inputs (voltages) are not measured. Then, unmeasured voltage of any zone can be estimated as follows:

$$u_1 = i_1 Z_L + u_2 \quad (11)$$

where

- Z_L is the line impedance
- u_1 is the unmeasured voltage
- u_2 is the measured voltage
- i_1 is the line current.

In some cases, not all currents can be measured and then will be estimated using KVL and KCL. To reduce the system cost, the ordinary measurements of current and voltage (from CTs and VTs) can be used instead of PMUs which are more expensive. Measured quantities may need to be converted to digital (A/D converter) if digital communication is used.

4.3. Protecting transformers using observer

Power transformers can be protected against internal faults using an observer technique. By dealing with the transformer impedance and measuring primary or secondary current, and primary and secondary voltages, any internal fault can be detected through the residual as shown in Figure 5.

To design the observer, voltage, current, and impedance should be transformed to one side and dealing with these quantities as in (1). In this case, the differential equation related to the circuit shown in Figure 5a will be

$$\frac{di_1}{dt} = \frac{-r}{L} i_1 + \frac{1}{L} (u_1 - \frac{1}{n} u_2) \quad (12)$$

and then the observer-based relay can be developed as in (4), as shown in Figure 5b. Internal faults can be defined as faults that occur in the region bounded with current and voltage measurement transformers. Therefore, the internal faults would appear in the observer's residual.

Three-phase transformers can be designed to use different connections (vector groups), some of which produce phase shifts between primary and secondary windings. This phase shift should be taken into consideration when transforming voltage from side to another. Sometimes, a transformer and the feeder section on one side of it are protected together, in a single zone; in such cases, the line impedance should be included so that the observer can protect the line and the transformer together.

4.4. Backup protection

While transmission systems always have multiple levels of backup protection, this is sometimes provided in distribution systems as well, using time graded overcurrent settings to provide backup protection in the event of failure of primary relays. In radial distribution systems, fuses are often used, and time coordination is applied even on fuses to provide backup protection. However, fuses are unsuitable for use in microgrids because they cannot adapt to different modes of operation or to bidirectional flows. The proposed observer-based protection system is suitable for use at all feeder levels in a microgrid, and these too are amenable to backup protection schemes.

In the proposed protection system, earth faults can be detected by phase observers of adjacent zones and therefore can be considered as backup protection for the faulted zone. Phase faults on the other hand cannot be detected by observers of adjacent zones; hence a back up observer is needed. A backup observer can be designed to cover two zones together and upon occurrence of a fault it detects and confirms the faulted zone and phase. Backup zone can protect two main zones together and may overlap with another backup zone as shown in Figure 1a. Following the steps in section 3, a backup zone is found and load values located inside it can be adjusted as limits

Table I. Zones' boundary nodes.

Zone	Boundary nodes
A	836–840
B	834–848
C	836–838
D	834–836
E	834–858
F	832–854
G	824–854
H	816–824
I	816–822
J	824–826
K	808–816
L	808–810
M	800–808
N	858–864
P	832–858
T	832–890

Table II. $f(x)$ constraints of IEEE 34 node.

$f_1 = x_1 + x_2 \geq 1$	$f_{10} = x_8 + x_{10} + x_{11} + x_{12} \geq 1$
$f_2 = x_1 + x_2 + x_3 + x_4 \geq 1$	$f_{11} = x_{10} + x_{11} \geq 1$
$f_3 = x_2 + x_3 \geq 1$	$f_{12} = x_{10} + x_{12} + x_{13} + x_{14} \geq 1$
$f_4 = x_2 + x_4 + x_5 + x_6 \geq 1$	$f_{13} = x_{12} + x_{13} \geq 1$
$f_5 = x_4 + x_5 \geq 1$	$f_{14} = x_{12} + x_{14} + x_{15} + x_{16} \geq 1$
$f_6 = x_4 + x_6 + x_7 + x_8 \geq 1$	$f_{15} = x_{14} + x_{15} \geq 1$
$f_7 = x_6 + x_7 \geq 1$	$f_{16} = x_{14} + x_{16} + x_{17} + x_{18} \geq 1$
$f_8 = x_6 + x_8 + x_9 + x_{10} \geq 1$	$f_{17} = x_{16} + x_{17} \geq 1$
$f_9 = x_8 + x_9 \geq 1$	$f_{18} = x_{16} + x_{18} \geq 1$

Where x_i is the observable PMU or sensor which is installed at bus i and has non-zero entry.

(thresholds) in phase residuals of the backup zone. Trip times for backup zones should be equal, but larger than that of the main zone.

4.5. Multi-zone protection

For centralized protection system, a multi-input-multi-output (mimo) state space representation should be constructed, encompassing all the zones of the microgrid system. This representation needs to incorporate the differential equations that express the dynamic behavior of the electrical power system; therefore, these equations are considered the infrastructure of mimo observer-based protection system as shown in Figure 1. In this work, the line currents are the states; hence, in order to reduce the number of current transformers in the microgrid, unmeasured states could be estimated. For system inputs, measured or estimated values of end voltages can be used.

Multi-zone protection is constructed using several single observers, describing all phase and earth fault observers of protected zones, as discussed in section 3. When constructed as shown in Figure 6, only the faulted phase and zone will have non-zero residual.

4.6. Selectivity of proposed protection system

The proposed system is able to identify in-zone faults correctly, regardless of whether the microgrid is operating in grid-connected or islanded mode. The only difference between these modes is in the magnitude of the residual; the presence of a residual indicates a fault within the zone, regardless of magnitude. In this protection scheme, it is recommended to place DGs and loads outside the observer zones, as shown in Figure 1. This ensures that DG injections and load variations do not create residuals. In the event that some load points are included in a zone of protection in order to reduce the number of measurements, a threshold should be set based on the maximum load. However, this should be performed only in cases where it is ascertained that sufficient discrimination can be achieved between high loads and low fault currents.

5. CASE STUDY

The observer-based protection system is tested using the IEEE 34 node test feeder shown in Figure 7. With the embedded generation as shown, this configuration represents a microgrid. The DGs are connected to the test feeder at voltage level of 24.9 kV, 60 Hz, and loads are distributed as well. All neutrals of generators are solidly grounded. The test feeder is divided into zones as shown in Figure 7. Positive and zero sequence impedances used in this test feeder are calculated using the formula:

$$Z_+ = Z_s - Z_m \quad (13)$$

$$Z_0 = Z_s + 2Z_m \quad (14)$$

In this research, the method of minimized PMU (sensor) placement is implemented, as explained in [12]. This system is divided into 17 zones, as shown in Figure 7 and Table I. Hence, the required measurements (current and voltage) should be placed at the 18 nodes that lie at the boundaries of the zones, as listed on Table I. A connectivity matrix is constructed as follows:

$$A_{k,m} = \begin{cases} 1 & \text{if } k = m \\ 1 & \text{if } k \text{ and } m \text{ are connected} \\ 0 & \text{otherwise} \end{cases} \quad (15)$$

The construction of A is similar to that of the bus admittance matrix, but with binary entries. The matrix A has 18 columns and 18 rows, and the constraints $f(x)$ given in (10) are as shown in Table II.

In Table II, the operator “+” is used as the logical “OR” and “ ≥ 1 ” means that at least one of the variables appearing in the sum will be non-zero. For instance, bus is 800 observable when for f_1 at least one PMU (measurements) is installed at bus 800 or 808 for minimum placement. For the minimum observability of bus 808 (f_2), PMU (or sensor) can be installed at 800, 808, 810, or 816. It is clear from the constraints that the common nodes are: 808, 816, 824, 854, 832, 858, 834, and 836. Therefore, only

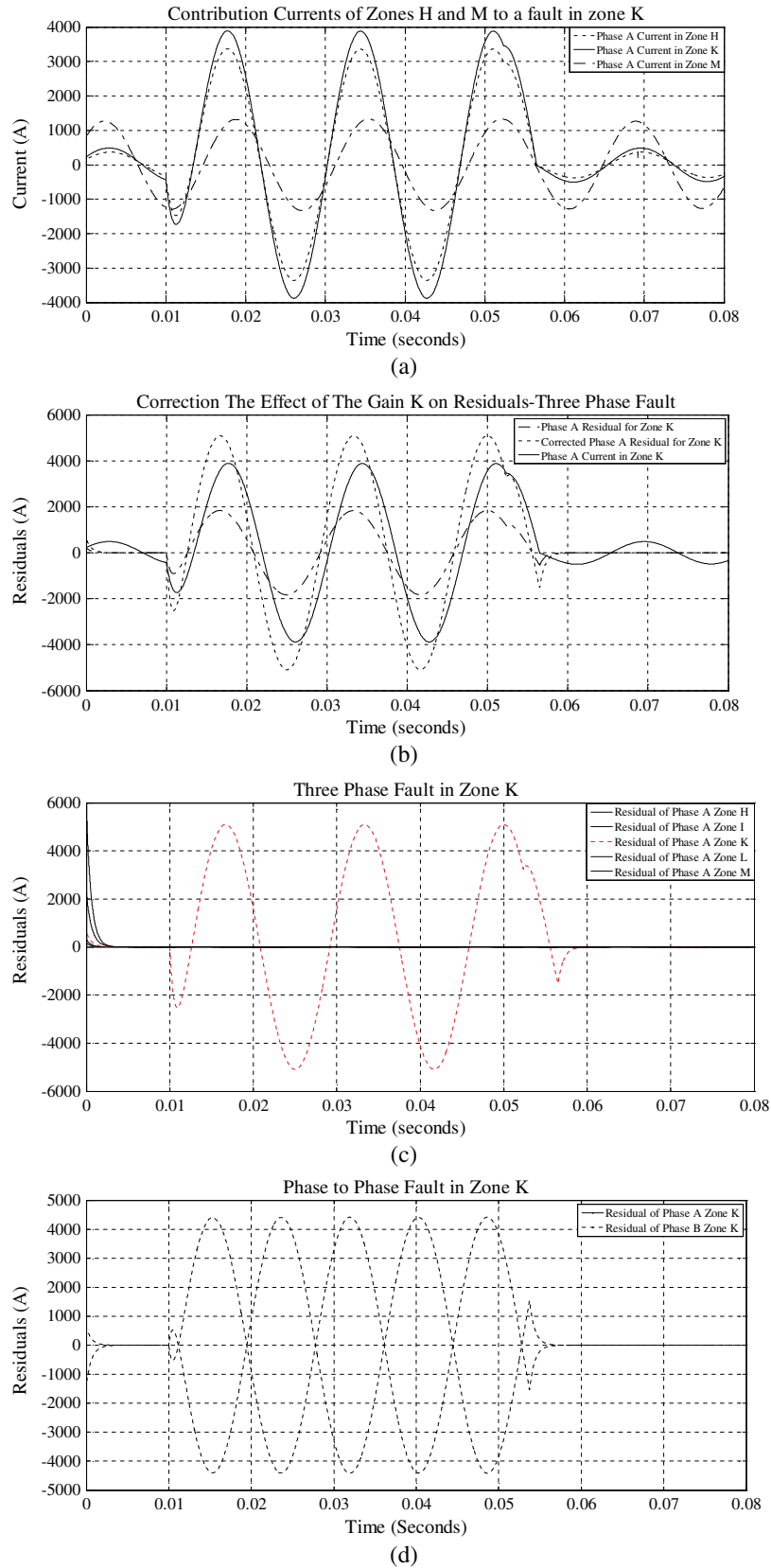


Figure 8. Three-phase fault. (a) Line contribution currents, (b) phase residual gain correction, (c) phase observer residuals, and (d) phase to phase fault.

eight PMUs need be placed on the IEEE 34 bus system to satisfy the observability condition. The total cost of the placed PMUs can be calculated using (10); hence, in this case, the total cost is $8w_i$.

A complete protection system is designed for all zones of the test feeder; each zone is protected by three-phase observers and one earth fault observer.

The definition of the contribution currents is explained in Figure 8a which shows currents that pass from the neighboring zones (H and M) toward the faulted zone (K). To avoid the effect of observer gain k , the approach presented in [16], as described by (9), has been implemented on the observer

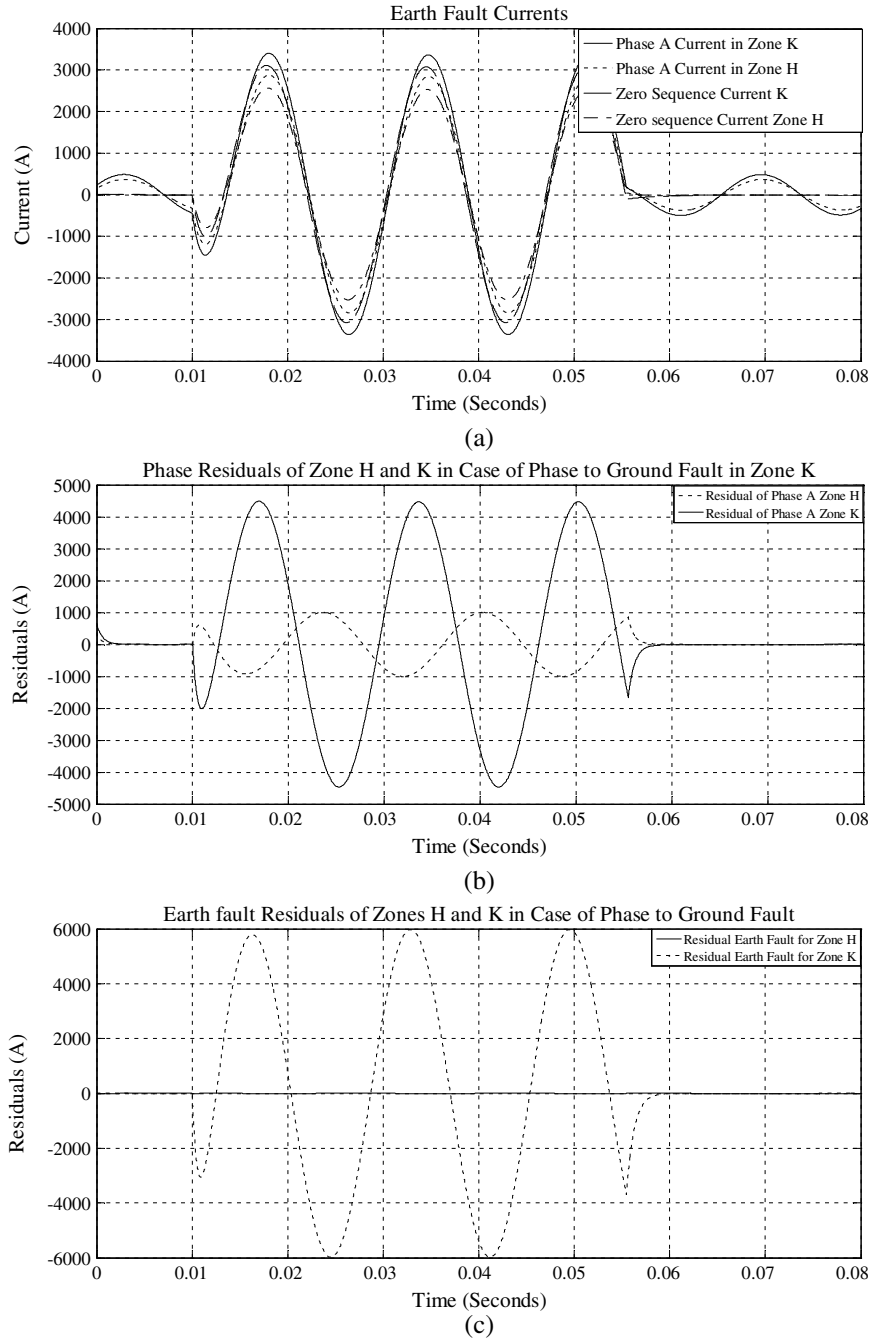


Figure 9. Single line to ground fault in zone K, (a) currents in zones K and H, (b) phase residuals of zones K and H, (c) Earth fault residuals of zones K and H.

residuals. Therefore, the residuals values are more accurate and approximately equal to the short circuit current values once a short circuit is applied as shown in Figure 8b.

For the purpose of illustration, results are shown in this work for the area between node 800 and node 824. This area is divided into zones as follows: H (node 816 to 824), I (node 816 to 822), K (node 808 to 816), L (node 808 to 810), and M (node 800 to 808). Faults are applied in the zone K and the behavior of observers in the other zones is examined. As shown in Figure 8c, when a three-phase fault is applied in the zone K (which is fed from the neighboring zones), only the three-phase observers belonging to zone K can detect the fault. To examine the protection system behavior with all kinds of faults, a phase to phase fault is applied to the zone K and only two faulted phase observers (phase *a* and *b*) in zone K are found to detect the fault, as shown in Figure 8d.

Simulation results are used to demonstrate the observer's performance in loading case and fault case. The simulated observers are only single phase observers. In the loading case, none of the observers can detect the load currents except the observer for the zone in which the load is located.

Ground fault are more complicated than phase faults since the zero sequence impedance is involved in the short circuit paths. Thus, phase observers can detect earth fault even if they are in other zones (as shown in Figure 9b), but only the earth fault observer of the zone K can detect the ground fault in zone K. Earth fault is instantaneous and much faster than phase fault observers, so it will trip before phase fault observers respond, as shown in Figure 9c. When a double phase to ground fault is applied, the earth fault observer detects the fault, as shown in Figure 10.

To examine the behavior of the protection system during high impedance faults, a single line to ground fault is applied through a 10 ohm resistance. As shown in Figure 11, the earth fault observer can detect the fault even if it is through high impedance.

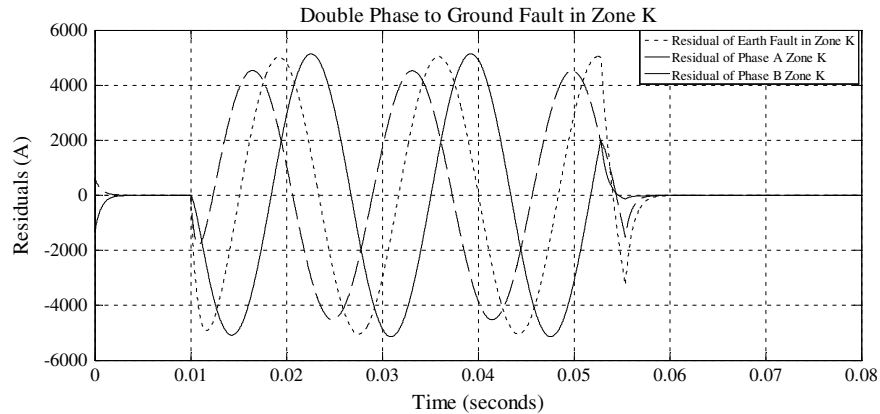


Figure 10. Phase and earth fault residuals of zone K in case of double phase to ground fault in zone K.

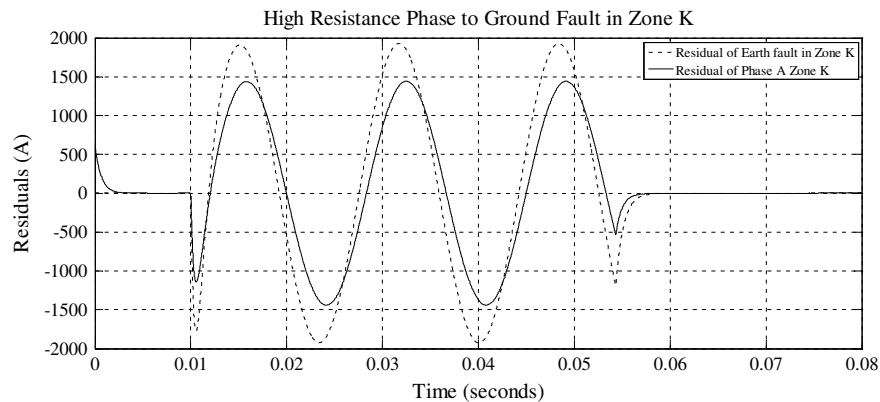


Figure 11. High resistance single line to ground fault in zone K.

The effectiveness of the proposed method in protecting power transformers is also demonstrated. A fault is simulated at the transformer between nodes 832 and 888. The transformer data is shown in Table III and the circuit used for the ATP simulation is illustrated in Figure 12a. The protection system is tested in normal state and with a single line to ground fault. In the normal state, the observer residual is zero as shown in Figure 12b, while in case of fault, this residual has value as shown in Figure 12c. The observer was also tested for out-of-zone (zone of protection) faults.

Table III. IEEE 34 node, transformer data.

MVA	kV-high	kV-low	R-%	X-%
0.5	24.9	4.16	1.9	4.08

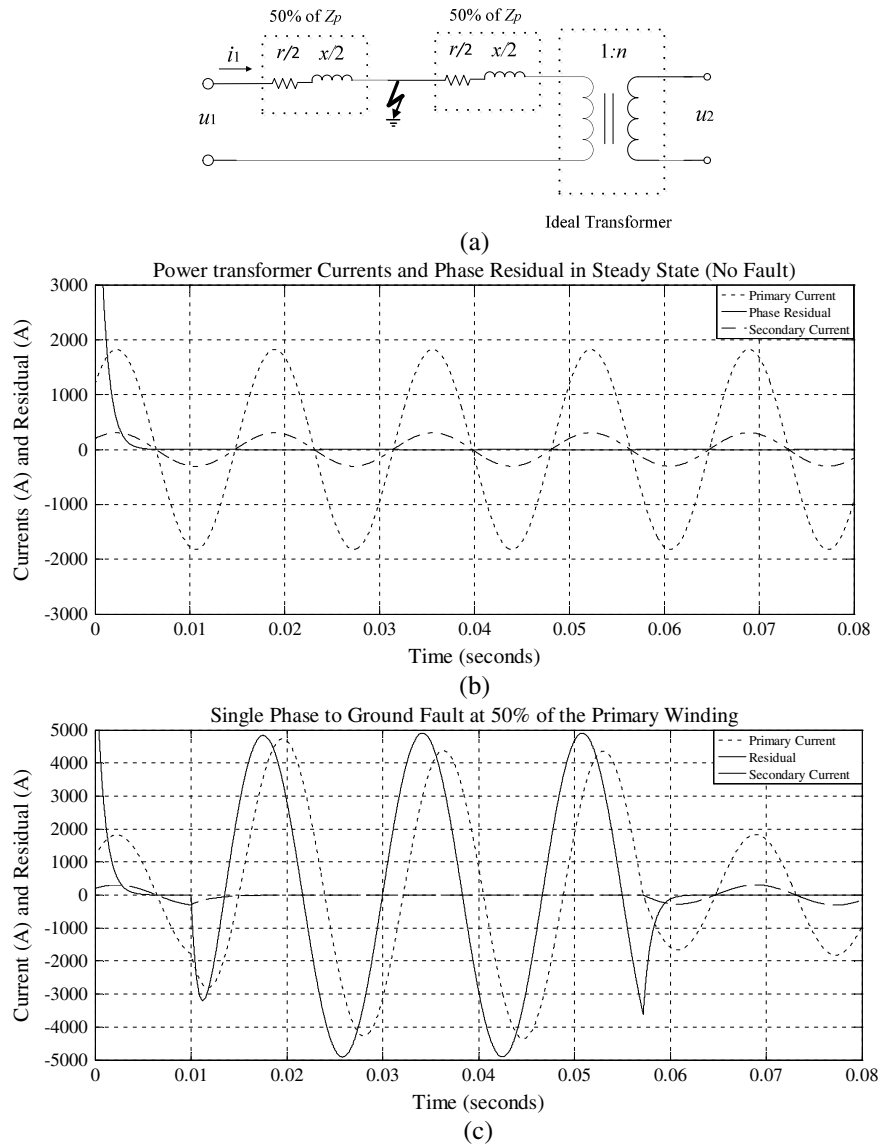


Figure 12. (a) System used in transformer fault simulation; (b) observer behavior in steady state; (c) observer behavior for single line to ground fault at 50% of the primary winding of power transformer.

6. DISCUSSION AND CONCLUSION

In this paper, a novel protection system for microgrids has been presented. The proposed method uses state observers for fault detection and identification, and the scheme can be implemented in a centralized or decentralized manner. The system was simulated using ATP and the results obtained demonstrated the effectiveness of the method. The system can detect both phase and earth faults. Phase observers are able to detect phase and earth faults, but earth fault observer detects only ground faults. By adjusting the trip time of earth fault observer to a value less than that of phase observer, the faulted zone can be identified and isolated. Earth faults occur far more frequently than phase faults; statistics showed that earth faults comprise about 90% of all faults. The proposed method is shown to be capable of protecting not only feeders but power transformers as well.

In cases where a protected zone includes one or more load points, (which occurs when some load nodes are skipped to reduce the number of measurements,) limits (thresholds) must be applied on the residual of the phase observer so that the protection system will trip for values larger than the load. This applies only to phase observers.

Not only is the proposed protection system economical to build and flexible to configure, the use of minimum measurement placement makes it even more cost effective.

7. LIST OF SYMBOLS AND ABBREVIATIONS

7.1. Symbols

R	Line resistance
L	Line inductance
u	Voltage
i	Current
x	Vector of state variables
$\hat{x}$	Estimated value of x
y	Vector of output variables
A	Coefficient matrix for state variables
B	Coefficient matrix for control variables
C	Coefficient matrix for output variables
k	Gain
e	Error
λ	Eigenvalue
L	Laplace transform
s	Laplace variable
I	Identity matrix
f_L	Fault
T	Time
Z	Impedance
n	Transformer turns ratio

7.2. Abbreviations

PMU	Phasor measurement unit
w_i	Cost of PMU
CT	Current transformer
VT	Voltage transformer
DG	Distributed generator

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